METHOD OF AND COMPOSITIONS FOR IMMUNIZATION WITH THE *PSEUDOMONAS* V ANTIGEN

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of U.S. Serial No. 09/448,339, filed November 23, 1999 and claims priority to U.S. Serial No. 60/109,952, filed November 25, 1998 and U.S. Serial No. 60/126,794, filed March 30,

5   1999, all of which are incorporated by reference herein.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

BACKGROUND OF THE INVENTION

Pseudomonas aeruginosa is an opportunistic bacterial pathogen that is capable of causing fatal acute lung infections in critically ill individuals (1).

15   The ability of the bacterium to damage the lung epithelium has been linked with the expression of toxins that are directly injected into eukaryotic cells via a type III-mediated secretion and translocation mechanism (2, 3).

The proteins encoded by the *P. aeruginosa* type III secretion and translocation apparatus demonstrate a high level of amino acid identity with

20   members of the *Yersinia* Yop regulon (4-6). Of all the type III systems discovered in Gram-negative bacteria, only *P. aeruginosa* possesses a homologue to the *Yersinia* V antigen, PcrV (see 6 for review of type III systems). Homologous proteins to the secretion and translocation apparatus are encoded by both plant and animal pathogenic bacteria. These organisms

25   include human pathogens such as *Salmonella typhimurium*, *Shigella flexneri*,

Enteropathogenic E. coli, Chlamydia spp., and plant pathogens such as *Xanthamonas campestris, Pseudomonas syringae, Erwinia amylovora* and *Ralstonia solanacearum.* However, only *P. aeruginosa* and *Yersinia* encode the V antigen.

5   Yahr, et al., 1997, discloses the sequence of the operon encoding PcrV and compares the sequence to the LcrV protein. Thus, the amino acid sequence of PcrV is known and is available under accession number AF010149 of GenBank.

SUMMARY OF THE INVENTION

10   The present invention involves methods and compositions developed from our observation that the *Pseudomonas* V antigen can be used to protect animals from a lethal lung infection.

In one embodiment, the present invention is a method of inhibiting *Pseudomonas* infection comprising inoculating a patient with an effective

15   amount of PcrV antigen. In another embodiment, DNA encoding PcrV is used as a gene vaccine.

In one preferred embodiment, the antigen is expressed as a recombinant protein and used to immunize patients at risk.

Preferably, the patient is completely protected from infection.

20   In another embodiment, the DNA encoding PcrV (called *pcrV*) or a DNA fragment may be used diagnostically to detect *P. aeruginosa* infection.

In another embodiment, the recombinant protein (rPcrV) is used diagnostically to detect antibodies from patients. Patient antibody response to PcrV may be associated with prognosis. Therefore, in this embodiment the

25   recombinant protein is used as a prognostic indicator by measuring the patient's antibody titer.

The present invention also provides a method for inhibiting a *Pseudomonas* infection in an individual by contacting the individual with an effective amount of a PcrV inhibitor, in particular with a PcrV antibody, antibody derivative or fragment, or antibody mimic. PcrV antibodies, antibody

5   derivatives and antibody fragments are also provided.

It is an object of the present invention to actively and passively immunize a patient against Pseudomonas infection.

It is another object of the present invention to diagnostically detect the *P. aeruginosa* infection.

10   It is another object of the present invention to diagnostically detect antibodies from *Pseudomonas* patients.

Other objects, features and advantages of the present invention will become apparent to one of skill in the art after review of the specification, claims and drawings.

DESCRIPTION OF THE DRAWINGS

15   Figs. 1A and 1B are a stained gel (Fig. 1A) and Western blot (Fig. 1B) illustrating the phenotypic analysis of PA103ΔpcrV.

Figs. 2A and 2B are a graph (Fig. 2A) and set of bar graphs (Fig. 2B) illustrating the survival and lung injury of *P. aeruginosa* parental and mutant

20   strains.

Figs. 3A and 3B are a graph (Fig. 3A) and a set of bar graphs (Fig. 3B) illustrating the effect of immunization on survival, lung injury, and bacterial colonization.

Fig. 4 is a graph of the number of animals surviving a challenge with 5

25   x 10^5 CFU/mouse of strain PA103 after passive administration of polyclonal IgG specific for PcrV, ExoU, PopD or control IgG from an unimmunized animal.

Fig. 5 is a graph (Fig. 5A) and a set of bar graphs (Fig. 5B) illustrating survival and protection from lung injury by concomitant administration of IgG to different bacterial antigens and bacterial challenge. One-way ANOVA for lung injury, p=0.026, and lung edema, p<0.0005.

5   Figs. 6A and B are printouts of SEQ ID NOs:1 and 2 with additional explanatory information. Fig. 6A is SEQ ID NO:1. Fig. 6B is SEQ ID NO:2.

Fig. 7 is a printout of SEQ ID NOs:3 and 4 with additional explanatory information.

DESCRIPTION OF THE INVENTION

10   We disclose herein that PcrV has a novel regulatory effect on expression of the type III secreted products, is involved in the translocation of type III toxins, and is the first antigen that protects against lung injury induced by *P. aeruginosa* infection. Vaccination against PcrV prior to the airspace

15   instillation of anti-PcrV IgG not only ensured the survival of challenged animals but also decreased lung inflammation and injury caused by the bacteria.

LcrV, or the V antigen, is a multifunctional protein that regulates secretion/translocation of the Yop effector proteins and plays an extracellular

20   role in pathogenesis by altering the host cytokine response to *Yersinia* infection (7-11). The only known homologue of this critical pathogenic factor is an extracellular protein encoded by *P. aeruginosa*, termed PcrV.

One embodiment of the present invention is a method of moderating or inhibiting a *Pseudomonas* infection by immunizing a patient with an effective

25   amount of the PcrV antigen. By "effective amount" we mean an amount of PcrV antigen effective to show some moderation or inhibition of *Pseudomonas* infection as compared to control subjects or animals who have not been treated with the antigen.

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By "moderating" we mean that infection is inhibited by at least fifty percent compared to a non-immunized animal. Preferably, infection is completely prevented. A quantitative assessment of infection would preferably include the examination of the amount of bacteria in the

5   bloodstream or pleural fluids and/or an examination of lung injury parameters. For example, the absence of bacteria in the bloodstream or pleural fluids would indicate prevention of infection. A reduction in lung injury parameters would indicate that infection is moderated.

Infection could be quantitatively assessed by several other clinical

10   indicators, including the reduction of bacterial load in the sputum, blood or pleural fluids, reduction in the size of the infiltrate, oxygenation improvement, reduction in the length of time on mechanical ventilation, reduction in fever and reduction in white blood cell count.

By "PcrV antigen" we mean that portion or fragment of the PcrV protein

15   that is necessary to invoke an immune response which prevents or moderates infection. We have used the full-length PcrV protein as an antigen to induce protection. Additionally, we have mapped the protective epitope to the fragment comprising amino acids 144-257 of PcrV. To define the epitope, monoclonal antibodies that protected against infection and cytotoxicity were

20   tested for binding to progressively smaller forms of recombinant PcrV. (By "recombinant PcrV" or "rPcrV" we mean the protein produced from a PcrV gene that has been placed in a non-native host.) This protection localized the region.

The PcrV antigen may be most easily obtained by the method we

25   used, commercially available bacterial expression plasmid pet16b from Novagen. The pcrV gene was first cloned from the *P. aeruginosa* chromosome as part of an operon. The coding region was amplified and inserted into two different vectors. One vector is for expression from *P.*

aeruginosa as shown in Fig. 1. This is a vector from Herbert Schweizer (reference 19) which we modified to contain an appropriate promoter sequence such that PcrV expression is coordinately regulated with the rest of the delivery and intoxication apparatus of the bacterium. The second

5   plasmid, pET16b, is for expression and purification purposes from *E. coli.*

The advantage of this system is that we do not have to worry about contaminating *P. aeruginosa* proteins, the protein is produced in great abundance, and there is a one-step purification process. In this situation the PcrV coding region is amplified to be cloned in frame with a histidine tag

10   provided on the pET16b vector. The multiple histidine residues fused to the amino terminus of PcrV allow affinity chromatography using a nickel-NTA column. Therefore, a preferable PcrV antigen is a recombinant version of the natural PcrV protein.

Immunization may be done systemically or intranasally. Immunization

15   of these individuals would preferably start during normal vaccination procedures for other childhood diseases. We would predict long-lived protection with booster doses probably around ages 5 and 10.

In another embodiment, one would use DNA encoding the PcrV protein or the complement of this DNA to diagnostically detect *P. aeruginosa*

20   infection. One would obtain the DNA sequence of the PcrV antigen at GenBank AF010149. The coding region for PcrV is at nucleotides 626-1510. One may also choose to use a fragment of this coding region or complement of this fragment. A successful probe is one that will hybridize specifically to the PcrV DNA and not to other regions.

25   One would preferably use a hybridization probe of at least 40 continuous nucleotides within the antigen sequence or two primers of at least 25 continuous nucleotides within the sequence. One skilled in the art would appreciate that many standard forms of nucleic acid diagnostic techniques

would be suitable, for example, hybridization of the single-stranded 40 nucleotide probe to DNA or RNA extracted from a patient's sputum. In another example, patient's sputum would be used as a source for bacterial DNA or RNA to serve as a template for the PCR or RT-PCR reaction,

5   respectively.

One would also determine *Pseudomonas aeruginosa* infection in an individual by contacting a sample obtained from the individual with an antibody specific for PcrV and correlating enhanced antibody binding as compared with a control sample with *Pseudomonas aeruginosa* infection in

10   the individual.

In an additional embodiment, the DNA encoding PcrV is used as a gene vaccine using standard molecular biological methods. For example, one could review the following references for techniques known to those of skill in the art: Davis, H.L., et al., "DNA vaccine for hepatitis B: Evidence for

15   immunogenicity in chimpanzees and comparison with other vaccines," Proc. Natl. Acad. Sci. 93:7213-7218, 1996; Barry, M.A., et al., "Protection against mycoplasma infection using expression-library immunization," Nature 377:632-635, 1995; Xiang, Z.Q., et al., "Immune responses to nucleic acid vaccines to rabies virus," Virology 209:569-579, 1995. By "effective amount"

20   of a gene vaccine, we mean an amount of vaccine effective to moderate or eliminate *Pseudomonas* infection or *Pseudomonas* infection symptoms.

The protein or antigen could also be used diagnostically to detect antibodies in patients and, thus, predict the patient's infection status. One would preferably contact a sample obtained from an individual suspected of

25   *Pseudomonas* infection with the PcrV protein or fragment thereof and detect protein/antibody binding. One would then correlate enhanced antibody binding (as compared with a control sample) with *Pseudomonas aeruginosa*

infection in the individual. One could also use the PcrV antibody or antibody fragments therapeutically.

In another embodiment, the invention is the use of the antibody sequence (which we report below and in SEQ ID NOs:1-4) to produce

5   recombinant single chain antibodies that may block PcrV and could also utilize the sequence in gene delivery experiments, where one would deliver eukaryotic vectors that will then lead to the production of single chain antibodies in animals for prolonged periods. The sequence could also be utilized to humanize the murine monoclonal antibody to produce a product

10   that can be utilized in human patient care.

Once the antibody is safe for human use, one could: (a) administer it systemically and (b) administer it into the lungs as either a preventative treatment or as a therapy. In order to use the PcrV antibody in humans, the antibody is preferably "humanized". In general, once the monoclonal

15   antibody is obtained the heavy and light chain variable regions are cloned. These cloned fragments are then inserted into a human antibody backbone (constant regions). Thus, we can control the class of antibody (IgG, IgA, etc.) in addition to providing the binding specificity.

For use in the present invention, the PcrV antibody may be a

20   monoclonal antibody or polyclonal. The antibodies may be human or humanized, particularly for therapeutic applications. Antibody fragments or derivatives, such as an Fab, F(ab')$_2$ or Fv, may also be used. Single-chain antibodies, for example as described in Huston, et al. (Int. Rev. Immunol. 10:195-217, 1993) may also find use in the methods described herein. By

25   "effective amount" of the PcrV antibody or antibody fragment we mean an amount sufficient to moderate or eliminate Pseudomonas infection or infection symptoms.

Preferably, human or humanized monoclonal or polyclonal antibodies to PcrV are administered to prevent or treat infections with *P. aeruginosa*. In patients at high risk for *P. aeruginosa* infection, antibodies could be administered for prevention of infection. In addition, antibodies may be

5   administered after the onset of infection to treat the infection. In this case, antibodies can be administered alone or in combination with antibiotics. Administration of antibodies in conjunction with antibiotics may allow the administration of shorter courses or lower doses of antibiotics, thereby decreasing the risk of emergence of antibiotic-resistant organisms.

10   We envision at least three types of hypothetical patients: (1) A healthy individual at risk of serious injury or burn (fire fighter, military personnel, police) would be immunized with the vaccine by a methodology (either injection or intranasal) that would give long-lived protection. A booster would be given on admission (intramuscular injection) to the hospital after injury. (2)

15   A patient who is being subjected to mechanical ventilation. (3) A patient who has been genetically diagnosed with cystic fibrosis.

In addition to PcrV antibodies and antibody fragments, small molecule peptidomimetics or non-peptide mimetics can be designed to mimic the action of the PcrV antibodies in inhibiting or modulating *Pseudomonas* infection,

20   presumably by interfering with the action of PcrV. Methods for designing such small molecule mimics are well known (see, for example, Ripka and Rich, Curr. Opin. Chem. Biol. 2:441-452, 1998; Huang, et al., Biopolymers 43:367-382, 1997; al-Obeidi, et al., Mol. Biotechnol. 9:205-223, 1998). Small molecule inhibitors that are designed based on the PcrV antibody may be

25   screened for the ability to interfere with the PcrV-PcrV antibody binding interaction. Candidate small molecules exhibiting activity in such an assay may be optimized by methods that are well known in the art, including for example, *in vitro* screening assays, and further refined in *in vivo* assays for

inhibition or modulation of *Pseudomonas* infection by any of the methods described herein or as are well known in the art. Such small molecule inhibitors of PcrV action should be useful in the present method for inhibiting or modulating a *Pseudomonas* infection.

5   In another aspect of the present invention, PcrV protein may be used to identify a PcrV receptor which may be present in the host cells, particularly in human cells, more particularly in human epithelial cells or macrophages. Identification of a PcrV receptor allows for the screening of small molecule libraries, for example combinatorial libraries, for candidates that interfere with

10   PcrV binding. Such molecules may also be useful in a method to inhibit or modulate a *Pseudomonas* infection.

Our first attempts at receptor identification will be to use PcrV in pull-down experiments. PcrV will be fused to glutathione S-transferase (GST) and attached to column matrix for affinity chromatography of solubilized cellular

15   extracts. Proteins binding specifically to PcrV will be eluted and subjected to amino terminal sequencing for identification. In parallel experiments PcrV will be subjected to yeast two-hybrid analysis. In this case PcrV is fused in frame with the DNA binding domain of Gal4. Once the clone is obtained it will be transformed into a suitable yeast host strain. The yeast strain containing the

20   Gal4PcrV construct will be transformed with a Hela cell cDNA bank cloned in frame with the Gal4 activation domain. Double transformants that complement the ability to utilize histidine and produce beta galactosidase (proteins that interact with PcrV) will be analyzed genetically and at the nucleotide sequence level. In case the receptor is a cellular glycolipid we will

25   utilize an overlay technique where glycolipids are separated by thin-layer chromatography and then probed with radiolabeled bacteria. The binding to specific components will be monitored by autoradiography. Similarly, epithelial and macrophage proteins will be separated by SDS-PAGE, blotted

onto nitrocellulose and overlaid with radiolabeled bacteria or labeled PcrV. Again, the protein components to which the bacteria bind are then identified by autoradiography.

Pseudomonas species are known to infect a wide spectrum of hosts within the animal kingdom and even within the plant kingdom. As will be apparent to one of ordinary skill in the art, the compositions and methods disclosed herein may have use across a wide range of organisms in inhibiting or modulating diseases or conditions resulting from infection by a *Pseudomonas* species. The compositions and methods of the present invention are described herein particularly for application to *Pseudomonas aeruginosa* but it is well within the competence of one of ordinary skill in the art to apply the methods taught herein to other species.

EXAMPLES

1. Role of PcrV in Cytotoxicity

To determine the role of PcrV in type III-mediated regulation/secretion, we constructed a nonpolar allele of PcrV and used the construct to replace the wild-type allele in *P. aeruginosa* strain PA103, a strain that is highly cytotoxic *in vitro* (3) and causes lung epithelial damage *in vivo* (12, 13). Cytotoxicity and lung injury are due to the production of a specific cytotoxin, ExoU (3).

PA103Δ*pcrV* was characterized by the expression of several extracellular products that are secreted by the *P. aeruginosa* type III system which include the ExoU cytotoxin (3), PcrV (5), and a protein required for the translocation of toxins, PopD (14). SDS-polyacrylamide gel electrophoresis of concentrated culture supernatants indicated that the parental strain, PA103 is induced for production and secretion of the type III proteins by growth in medium containing a chelator of calcium, nitrilotriacetic acid (NTA) (Fig. 1).

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When an expression clone encoding PcrV was provided in *trans* in the parental strain, extracellular protein production in response to the presence or absence of NTA is normal. PA103Δ*pcrV* exhibits a calcium blind phenotype; extracellular protein production is strongly induced in both the presence and

5   absence of NTA. These results suggest that the secretory system is fully functional but deregulated. This deregulated phenotype is in contrast to the calcium independent phenotype reported for an LcrV defective strain which fails to produce the extracellular Yops, grows at 37°C regardless of the presence or absence of calcium, and shows only partial induction of the Yops

10   (7). Complementing PA103Δ*pcrV* with a clone expressing wild-type PcrV restored normal regulation of extracellular protein production in response to NTA induction.

     To test the contribution of PcrV to *P. aeruginosa* pathogenesis, two infection models were used. In an *in vitro* model the parental and several

15   mutant derivative strains were compared for their ability to cause cytotoxicity in a CHO cell infection assay (3). The negative controls in this experiment included PA103*popD*::Ω, which has been previously shown to be defective in the translocation of type III virulence determinants (14) and PA103Δ*exoU*, which is non-cytotoxic due to the absence of ExoU production (3, 15).

20   After a 3 hour infection, CHO cells were unable to exclude trypan blue with the wild-type and Δ*pcrV* strain complemented with a plasmid construct expressing PcrV. Staining did not occur when CHO cells were infected with the negative control strains or with PA103Δ*pcrV* (data not shown). These results suggest that PcrV expression is required for cytotoxicity. Purified

25   recombinant PcrV was not cytotoxic when added exogenously to tissue culture cells. Since secretion of the type III proteins required for translocation was unaffected by the deletion of *pcrV* (Fig. 1A and B), PA103Δ*pcrV* appears to be defective in ExoU translocation.

Figs. 1A and 1B are a stained gel (Fig. 1A) and Western blot (Fig. 1B) illustrating the phenotypic analysis of PA103ΔpcrV. The parental and ΔpcrV derivatives, with and without a plasmid expressing PcrV in *trans*, were grown in the absence or presence of the inducer of type III secretion in *P.*

5   *aeruginosa*, nitrilotriacetic acid (NTA). The extracellular protein profile (Fig. 1A) was analyzed on a SDS-polyacrylamide gel (10%) stained with Coomassie blue. The migration of the *P. aeruginosa*-encoded type III proteins is indicated to the left and the migration of molecular weight markers is indicated on the right. Fig. 1B is a Western blot of a duplicate gel using

10   antibodies specific for ExoU, PcrV, and PopD and ^{125}I-Protein A to detect bound IgG.

Wild-type and mutant *P. aeruginosa* strains were tested in an acute lung infection model using low and high challenge doses of bacteria. Survival measurements indicated that PcrV and PopD were required to induce a lethal

15   infection (Fig. 2A). In experiments utilizing three independent measurements of lung injury (the flux of labeled albumin from the airspaces of the lung to the bloodstream, the flux of labeled albumin from the airspaces of the lung to the pleural fluids, and the wet/dry ratio, which measures lung edema) the degree of injury caused by PA103Δ*pcrV*, the vector control strain

20   (PA103Δ*pcrV*pUCP18), and PA103*popD*::Ω were no different than the uninfected control animals (Fig. 2B). Complementation of PA103Δ*pcrV* with *pcrV in trans* restored lung injury levels to those measured with the parental strain, PA103. Taken together these data indicate that PcrV expression is required for virulence of *P. aeruginosa* in the acute lung infection model and

25   that part of the function of PcrV appears to be linked to the ability to translocate type III effector proteins into eukaryotic cells.

Figs. 2A and 2B are a graph (Fig. 2A) and set of bar graphs (Fig. 2B) illustrating the survival and lung injury of *P. aeruginosa* parental and mutant

strains. Referring to Fig. 2A, mice were challenged with 5 x 10^5 cfu of each of the indicated strains and survival was monitored for one week. Referring to Fig. 2B, lung injury was assessed by the flux of labeled albumin from the airspaces of the lung to the blood (lung epithelial injury), to the pleural fluid

5   (pleural fluid) or by measuring the wet/dry ratio (lung edema). Two bacterial infectious doses were used as denoted by the solid and striped bars. Significant differences (*p<0.001) between control and test groups was determined by one-way ANOVA and Dunnet multiple comparison tests. The following abbreviations were used: PA103, parental wild-type strain; Δ*pcrV*,

10   PA103Δ*pcrV*; Δ*pcrV*pUCP*pcrV*, PA103Δ*pcrV* complemented with a plasmid expressing *PcrV*; Δ*pcrV*pUCP, PA103Δ*pcrV* with a vector control; *popD*::Ω, PA103*popD*::Ω, a translocation defective strain.

2.   Immunization with PcrV

To determine whether immunization with PcrV protected animals from

15   a lethal lung infection, recombinant PcrV (rPcrV) or ExoU (rExoU) were purified as histidine-tagged fusion proteins and used as antigens. Mice were immunized and subsequently challenged via their airspaces with a lethal dose of strain PA103. When survival was measured, both vaccines protected the mice (Fig 3A). When lung injury was assessed, only PcrV vaccinated animals

20   had significantly less epithelial damage and lung edema (Fig. 3B). Animals immunized with the PcrV vaccine also had significantly fewer bacteria in their lungs, suggesting that a blockade of the *Pseudomonas* V antigen may facilitate rapid clearance of bacteria from the lung, protecting the animals from severe epithelial injury (Fig. 3B).

25   Figs. 3A and 3B are a graph (Fig. 3A) and a set of bar graphs (Fig. 3B) illustrating the effect of immunization on survival, lung injury, and bacterial colonization. Referring to Fig. 3A, mice were immunized (PcrV, n=10; ExoU, n=5; control, n=10) as indicated and challenged with strain PA103 at 5 x10^5

CFU/animal. The percent of surviving animals was determined for one week; p<0.05 by the Mantel-Cox log rank test. Referring to Fig. 3B, lung injury assessment and bacterial colonization of vaccinated animals 4 hours after installation of PA103. Lung epithelial injury, lung edema, and bacterial

5   burden; PcrV, n=9; ExoU, n=4; and control, n=8. The final number of bacteria in the lung is indicated as the number on the Y axis x 10^4 CFU. Significant differences (*) for lung injury (p<0.01), lung edema (p<0.05), and bacterial numbers (p<0.05) as determined by Dunnet multiple comparison test. One-way ANOVA for lung injury, p=0.0005; lung edema, p=0.0437; bacterial

10   burden, p=0.0075.

To determine whether therapeutic intervention was possible, mice were passively immunized with preimmune rabbit IgG or rabbit IgG specific for rPcrV, rExoU, or rPopD one hour prior to airspace instillation of PA103 at a concentration of 5 x10^5 CFU/mouse. Antibodies to rPcrV provided complete

15   protection to a lethal infection (Fig. 4). Anti-rExoU IgG provided partial survival, which was significantly different from the administration of control IgG, although all the surviving animals appeared severely ill during the trial. Survival was not improved by the passive transfer of antibodies to another of the type III translocation proteins, PopD. From these results we conclude that

20   antibodies to PcrV are highly protective in the acute lung infection model and that PcrV may be exposed on the bacterial surface or in a soluble form that is available for antibody-antigen interactions.

Fig. 4 is a graph of the number of animals surviving a challenge with 5 x 10^5 CFU/mouse of strain PA103. Animals were pretreated with 100 µg of

25   immune IgG or control IgG from an unimmunized rabbit (rPcrV, preimmune serum). N=10 for each group; *p<0.05 versus control group for treatment with anti-PcrV and anti-ExoU IgG preparations by Mantel-Cox log rank test.

If PcrV is accessible for neutralization, then concomitant administration of the bacterial inoculum with anti-rPcrV IgG should completely protect against lung injury and lethality. IgG preparations were mixed with the inoculum (10-fold higher dose than the lethal inoculum) prior to instillation of

5   the bacteria into the lung and survival was measured. Only anti-rPcrV IgG was protective against this extreme infection (Fig. 5A). Lung injury was measured in animals infected with the normal lethal dose of 5×10^5 bacteria. The efflux of labeled albumin from the airspaces of the lung was only 3% more than uninfected controls (Fig. 5B) after co-administration of anti-rPcrV

10 IgG. The decreased efflux of labeled protein from the lung to the pleural fluids was the same as the uninfected controls when anti-PcrV was included with the inoculum. Curiously lung edema, as measured by the wet/dry ratio, was significantly reduced by the addition of either anti-rPcrV or anti-rPopD. (Fig. 5B). Thus, the concomitant administration of anti-rPcrV IgG with the

15 bacteria was even more effective in normalizing all the lung injury parameters than vaccination. These data support the accessibility of PcrV for antibody-mediated neutralization and document a clinically relevant decrease in lung injury; antibodies to PcrV may serve as therapeutic reagents in the treatment of severe nosocomial pneumonia caused by *Pseudomonas aeruginosa*.

20   Fig. 5 is a graph (Fig. 5A) and a set of bar graphs (Fig. 5B) illustrating survival and protection from lung injury by concomitant administration of IgG and bacterial challenge. IgG (5 µg) was mixed with either 5×10^6 (for survival assays, n=10 per group) or 5×10^5 (for the measurement of lung injury, n=4 to 6 animals per group) *P. aeruginosa* strain PA103. This mixture was instilled

25 into the lungs and survival (Fig. 5A) or lung injury (Fig. 5B) was assessed. For survival, *p<0.05 versus control IgG for anti-PcrV by the Mantel-Cox log rank test; for lung epithelial injury and lung edema *p<0.05 versus control IgG

by Dunnet multiple comparison test. One-way ANOVA for lung injury, p=0.026, and lung edema, p<0.0005.

In acute *P. aeruginosa* infections, the net effect of type III-mediated intoxication may be to promote the dissemination of the bacterium beyond the epithelium leading to infection of the pleural fluids, spleen, liver, and bloodstream. Blood-borne infections with *P. aeruginosa* from either acute ventilator-associated pneumonia or from burn wound infections can result in a 40-80% mortality rate in spite of aggressive antibiotic treatment (16). PcrV must be a component of the type III translocation complex in *P. aeruginosa*, as mutants defective in the production of this protein are unable to intoxicate CHO cells or cause lung epithelial injury even though they are able to produce and secrete the type III effectors and proteins required for translocation. Unlike PopD, which is also necessary for translocation, PcrV is accessible for antibody-mediated neutralization suggesting that antibodies may be useful therapeutic agents in acute infections.

3. <u>Methods for Examples 1 and 2</u>

<u>Construction of a nonpolar insertion in *PcrV* and complementation</u>. A 5.0-kb *Eco*RI-*Nsi*I restriction fragment encoding *pcrGVHpopBD* and flanking sequences was cloned into the allelic replacement vector pNOT19 (17). Two *Not*I sites (one within *pcrG* and one within *popB*) were removed from the inserted sequences by using the Sculptor mutagenesis system (Amersham). An internal *Sst*I restriction fragment was deleted from *pcrV*, resulting in an in-frame deletion of residues 17-221 (pNOTΔ*pcrV*). To select for integration of the plasmid, a gene encoding tetracycline resistance (TcΩ) was cloned into the *Hind*III site of the vector (pNOTΩΔpcrV). The MOB cassette (17) was added as a *Not*I fragment. Selection of merodiploids, resolution of plasmid sequences, and confirmation of allelic replacement was performed as previously described (18). A shuttle plasmid (pUCP, 19) was used to

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construct a clone to complement the *pcrV* deletion. The coding sequence for PcrV was amplified and cloned behind the control of the ExoS promoter region (20). The transcription of ExoS is coordinately regulated with the operons that control type III secretion and translocation in *P. aeruginosa* (2).

5   The nucleotide sequence was confirmed for each DNA construct involving site specific mutagenesis, PCR amplification, or in-frame deletion.

SDS-PAGE and Western blot analysis of secreted products. *P. aeruginosa* were grown under inducing (+NTA) or non-inducing conditions (-NTA) for expression of the type III secreted products (18). Cultures were

10   harvested based on optical density measurements at 540 nm and supernatant fractions were concentrated by the addition of a saturated solution of ammonium sulfate to a final concentration of 55%. Each lane of an SDS-polyacrylamide gel (11%) was loaded with 3 µl of a 20-fold concentrated supernatant and stained with Coomassie blue. An identical gel

15   was subjected to Western blot analysis as previously described (3-5) using a cocktail of rabbit antisera, which specifically recognizes ExoU, PopD, and PcrV. Protein A labeled with ^{125}I was used as a secondary reagent to identify bound IgG.

Infection models and lung injury assessments. Chinese Hamster

20   Ovary cells (CHO) were used in an *in vitro* infection model designed to measure cytotoxicity and type III translocation (21). Briefly, a bacterial inoculum was prepared in tissue culture medium without serum. CHO cells, which were propagated in serum containing medium, were washed and infected with various *P. aeruginosa* strains at a multiplicity of infection of 5:1.

25   Cultures were incubated under tissue culture conditions for 3 hours (37°C, 5% CO_2), washed, and stained with trypan blue. Permeability to the dye was determined from phase contrast photographs. Infection with the parental strain PA103, which expresses ExoU, results in trypan blue staining of

approximately 80% of the monolayer after 3 hours of incubation and complete destruction of the monolayer at 4-5 hours of incubation. Mouse infections and assessment of lung injury was performed as previously described (16). Briefly, male 8- to 12-week old pathogen-free BALB/c mice were purchased

5   from Simonsen Laboratories (Gilroy, CA) and housed in barrier conditions. The mice were briefly anesthetized with inhaled Metofane (methoxyflurane, Pitman-Moore, Mundelein, IL) and placed supine, at an angle of approximately 30°. Fifty microliters of the bacterial inoculum was instilled slowly into the left lobe using a modified 24 gauge animal feeding needle

10   (Popper & Sons, Inc., New Hyde Park, NY) inserted into the trachea via the oropharynx. When lung injury assessments were measured, 0.5 µCi of ^{131}I-labeled human serum albumin (Merck-Frosst, Quebec, Canada), 0.05 µg of anhydrous Evans blue in ml of Ringer's lactate with 5% mouse albumin were added to the instillate. After 4 hours of infection, the mice were anesthetized,

15   blood was collected by a carotid arterial puncture and median sternotomies were performed. The lungs, pleural fluids, tracheas, oropharynxes, stomachs, and livers were harvested, and the radioactivity was measured. The percentage of radioactive albumin that left the instilled lungs and entered the circulation or the pleural fluid was calculated by multiplying the counts

20   measured in the terminal blood samples (per ml) times the blood volume (body weight X 0.07). The wet-dry ratios of the lungs were determined by adding 1 ml of water to the lungs and homogenizing the mixture. Homogenates were placed in preweighed aluminum pans and dried to constant weight in an 80°C oven for three days. Lung homogenates were

25   also sequentially diluted and plated on sheep blood agar for quantitative assessment of bacteria.

<u>Production of rabbit antiserum to PcrV, PopD, and ExoU</u>. rPcrV, rPopD, and rExoU were produced as histidine tagged fusion proteins in

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pET16b and purified by nickel chromatography as previously described (22). Rabbits were injected intradermally (10 sites) with 300 µg of recombinant protein emulsified in Freund's complete adjuvant, boosted with antigen in Freund's incomplete adjuvant, and periodically bled at 7 day intervals. For

5   passive immunization, the IgG fraction was isolated using Protein A column chromatography (Pierce Chemicals, Rockford, IL). Mice were injected with 100 µg IgG (intraperitoneal injection) 1 hour before challenge with 5×10^5 CFU of strain PA103. For active immunization with rPcrV and rExoU, endotoxin was removed from protein preparations by extraction with 1%

10   Triton X-114 (23). Following the extractions, Triton X-114 was removed by Sephacryl S-200 chromatography. All vaccine preparations contained less than 1 ng of endotoxin per 40 µg of recombinant protein as determined by using a limulus amebocyte lysate assay (BioWhittaker, Walkersville, MD). BALB/c mice were injected subcutaneously with 10 µg of recombinant

15   proteins in Freund's complete adjuvant. At day 30 the mice were boosted with an additional 10 µg of antigen in Freund's incomplete adjuvant. On day 51 the mice were challenged by instillation of *P. aeruginosa* into their left lungs.

    4.   Synthesis of Monoclonal Antibodies

20   Mice were immunized with 10 µg of purified, LPS-free, recombinant PcrV in Freund's complete adjuvant and boosted two weeks later with the same dose of antigen emulsified in Freund's incomplete adjuvant. Immunizations were performed subcutaneously. Spleens were harvested from mice one week after booster doses of PcrV in Freund's incomplete

25   adjuvant.

    A single spleen was placed in 5 ml of tissue culture medium without serum, cut into pieces and gently homogenized. Large pieces of tissue were allowed to settle from the homogenate and the supernatant, single-cell

suspension was removed and subjected to centrifugation at 1200 rpm for 10 minutes. The pelleted cells were resuspended in 10 ml of a solution to lyse red blood cells for 5 minutes and subsequently underlaid with 10 ml of fetal bovine serum. The material was centrifuged at 1200 rpm for 8 minutes, the

5   supernatant was discarded and the cells were suspended in 30 ml of medium.

Spleenic cells and myeloma cells (P3x63Ag8.653) were harvested by centrifugation at 1200 rpm for 10 minutes, and each pellet was separately suspended in 10 ml of tissue culture medium. 10^8 spleen cells and 2×10^7 myeloma cells were mixed and pelleted together by centrifugation at 1200

10   rpm for 6 minutes. The supernatant was removed by aspiration and 1 ml of 35% polyethylene glycol (PEG) was added. The cells were suspended in this solution gently and centrifuged at 1000 rpm for 3 minutes. In some experiments centrifugation was eliminated.

Exactly 8 minutes after the addition of PEG, 25 ml of medium was

15   added and the cells were gently resuspended. Following a 5 minute 1200 rpm centrifugation step, the cell pellet was suspended at a density of 1×10^6 per ml in 30% conditioned medium and 70% complete medium (with serum). The cells were incubated overnight at 37°C. The next day the cells were harvested by centrifugation and suspended in 200 ml of 30% conditioned

20   medium and 70% complete medium with hypoxanthine, aminopterin and thymidine (HAT).

Approximately 0.2 ml of this cell suspension was added per well to ten 96-well plates (12 ml per 96 well plate). The density of the remaining cells was adjusted to 2.5×10^5 per ml and the cells were plated in the 96 well

25   format. Plates were screened microscopically for single colonies and supernatants were subsequently tested for antibody production by enzyme-linked immunosorbent assay using recombinant PcrV as the antigen. Clones

producing antibodies reactive to PcrV were subcultured to larger culture dishes and then isotyped.

The binding of antibodies was tested in an enzyme linked immunosorbent assay using recombinant PcrV as the antigen (histidine-tagged protein) coating the wells. Monoclonal antibodies were also tested in Western blot reactions using a *P. aeruginosa* supernatant containing native PcrV without the histidine tag.

5. Identification of PcrV Antigen

We obtained about three hundred cell lines producing antibodies that bound the tagged PcrV. These initial cell lines were preserved in liquid nitrogen for safekeeping. All cell lines were passaged to isolate stable clones. In conjunction with isolating stable clones we developed in *in vitro* assay as a correlate for protection against intoxication in animal infection models.

The hybridomas that were stable to passage and still produced antibodies reactive to PcrV in ELISA (approximately 80 cell lines) were subsequently tested in a Fluorescence Activated Cell Sorter using the following techniques and assumptions: We reasoned that if antibody is blocking the type III intoxication system, then in the presence of a monoclonal that blocks, fewer cells will be killed by our toxins. We exposed cells to each of the 80 monoclonal antibodies, added toxic bacteria, incubated, and then added a dye that is only permeable to dead cell DNA (propidium iodide). Excess dye was washed away and the cells were harvested, fixed, and analyzed by FACS. Dead cells would be fluorescent since the dye leaked in and stained DNA in the nucleus.

We found that if the cells were incubated with rabbit polyclonal anti-PcrV, mouse polyclonal anti-PcrV, or mab166 and bacteria, fewer cells died

than in controls with irrelevant polyclonal antibody (anti-PopD) or the other 78 monoclonal antibodies.

Mab 166 was specifically found to bind to the bacterially encoded type III-secreted factor termed PcrV. PcrV mediates the interaction of *P.* 5 *aeruginosa* and lung cells to facilitate the translocation of bacterial toxins that cause cellular death. This reaction is postulated to eliminate lung cells that are involved in the innate immune response to *P. aeruginosa*. The killing of these cells leaves the host epithelium open for *P. aeruginosa* colonization and spread to the pleural fluids and bloodstream. *P. aeruginosa*-encoded 10 antibiotic resistance makes effective treatment unlikely once the bacteria have entered the bloodstream.

The protection afforded by mab 166 pre- and post-bacterial instillation in animal models of acute lung infection with *P. aeruginosa* is significant. To design antibody treatment modalities for intervention in human *P. aeruginosa* 15 infections it will be necessary to produce either a human monoclonal antibody or to immunize at risk patients with the protective epitope of PcrV defined by mab 166. The goal of the work described below is to define the amino acid sequence of PcrV bound by mab 166.

Results

20 We used a molecular genetic approach to define the amino acid residues bound by mab 166. PcrV possesses 294 amino acids. The approach consisted of deleting parts of the molecule at the nucleotide sequence level using the polymerase chain reaction. Each product was cloned into a protein expression vector in frame with a gene encoding the 25 glutathione S transferase protein. This strategy ensured that deletions encoding small numbers of PcrV amino acids could be detected using Western or dot blot techniques. Control bacterial lysates encoding only

glutathione S transferase showed no reactivity to either our anti-PcrV polyclonal or mab 166 monoclonal antibody.

A total of 66 (with one full-length PcrV expression plasmid) clones were constructed, expressed, and tested for reactivity to rabbit polyclonal

5 anti-PcrV antisera. All but one clone bound to anti-PcrV rabbit antibody verifying that the expressed proteins were in-frame with PcrV. The one non-reactive clone was eliminated from the analysis. None of the C-terminal deletions (n = 5 constructs) bound mab 166 suggesting that the epitope was in the C-terminal half of the protein. Only one of the N-terminal truncation

10 proteins (n = 8 constructs) encoding PcrV amino acids (aa) 139-294 bound to mab 166. This experiment verified our hypothesis that the mab 166 epitope was encoded by the carboxyl terminal half of the protein. The remaining 51 constructs encoded various internal deletions of the molecule. Binding analysis tabulated in Table 1, below, demonstrated that the smallest epitope

15 recognized by mab 166 consists of aa 144-257 of PcrV.

TABLE 1

PcrV Epitope Mapping		
All proteins are amino-terminal tagged GST-PcrV truncates.		
Amino Acids	Binding to pAb	Binding to mAb 166
1-294 (full-length)	yes	yes
(C-term truncates)		
1-46	yes	no
1-76	yes	no
1-134	yes	no
1-172	yes	no
1-75 + 173-294	yes	no
(N-term truncates)		
139-294	yes	yes
148-294	yes	no
159-294	yes	no
164-294	yes	no
194-294	yes	no
261-294	yes	no
269-294	yes	no
278-294	yes	no
(internal fragments)		
139-191	yes	no
139-195	yes	no
139-234	yes	no
139-243	yes	no
139-256	yes	no
139-257	yes	yes; weak
139-258	yes	yes
139-259	yes	yes
139-260	yes	yes
139-261	yes	yes
139-262	yes	yes
139-263	yes	yes
139-264	yes	yes
139-265	yes	yes
139-266	yes	yes
139-274	yes	yes
139-281	yes	yes
140-266	yes	yes
141-266	yes	yes
142-266	yes	yes
143-266	yes	yes
144-266	yes	yes
145-266	yes	no
146-266	yes	no
147-266	yes	no

Amino Acids	Binding to pAb	Binding to mAb 166
148-170	no*	no
148-202	yes	no
159-202	yes	no
159-209	yes	no
159-216	yes	no
159-226	yes	no
159-234	yes	no
164-234	yes	no
164-243	yes	no
164-256	yes	no
164-266	yes	no
164-275	yes	no
164-281	yes	no
194-234	yes	no
194-243	yes	no
194-256	yes	no
194-266	yes	no
194-275	yes	no
194-281	yes	no
141-258	yes	yes; weak
142-258	NT**	yes
143-258	yes	yes
144-258	yes	yes
141-257	yes	yes
142-257	yes	yes
143-257	yes	yes
144-257	yes; weak	yes; weak

NOTES:
*Truncate 148-170 is the only one that is not recognized by the rabbit polyclonal control antibody.
**NT; Not Tested due to an insufficient amount of bacterial lysate.
-As predicted, pGEX-4T-2 vector control lysates were not recognized by either antibody.
-The smallest epitope of PcrV recognizable by mAb166 appears to consist of amino acids 144-257.

6.   Examination of PcrV-Specific Antibody

Methods:

Poly A+ RNA extraction: Hybridoma cell line m166 was cultured in complete Dulbeccos minimum essential medium with 4.5 g/L D-glucose, 10 mM HEPES, 50 µM 2-mercaptoethanol, 3 mM L-glutamine, and 10% heat-inactivated fetal calf serum, 100 U/mL penicillin and 100 µg/mL streptomycin sulfate. After the cells reached confluent state in a 75 cm^2 flask, the cells were harvested from centrifuging at 600 rpm for 5 minutes. The pellet of the cells was homogenized in 2 mL of TRIzol reagent (Life Technologies, Gaithersburg, MD), and total RNA (100 µg) was extracted after chloroform

fractionation, isopropanol precipitation and 70% ethanol wash. Poly A+ RNA (4 µg) was extracted with oligotex mRNA spin-column (Qiagen, Valencia, CA).

RNA oligo-capping: mRNA (250 ng) was incubated with calf intestinal

5 phosphatase at 50°C for 1 hour to dephosphorylate non-mRNA or truncated mRNA. After the reaction, phenol/chloroform extraction and ethanol precipitation was performed and the dephosphorylated RNA was incubated with tobacco acid pyrophosphatase at 37°C for 1 hour to remove the 5'-cap structure from full-length mRNA. After phenol/chloroform extractions and

10 ethanol precipitation, the synthetic RNA oligo (GeneRacer RNA Oligo, Invitrogen, Carlsbad, CA) was ligated to the decapped RNA with T4 RNA ligase at 37°C for 1 hour. After phenol/chloroform extraction and ethanol precipitation, the RNA was suspended in 13 µL diethylpyrocarbonate-treated water.

15 Reverse-transcribing mRNA: The RNA-oligo ligated, full-length mRNA (13 µL) was reverse-transcribed with 54 base the pair primer containing a dT tail of 18 nucleotides (GeneRacer Oligo dT, Invitrogen), and Avian myeloblastosis virus reverse transcriptase at 42°C for 1 hour in 20 µL reaction. After the reaction, the sample was diluted 4 times with sterile water.

20 Amplifying cDNA ends by polymerase chain reaction (PCR): One microliter of the cDNA was used for PCR. The 5' primer from the synthetic RNA oligo sequence (GeneRacer 5' Primer, Invitrogen) and the murine immunoglobulin gamma 2b chain CH1 region specific primer or the murine immunoglobulin kappa chain CL region specific primer were used. The

25 cycling parameters used for the PCR reaction was; 1) 94°C, 2 minutes, 1 cycle, 2) 94°C, 30 seconds and 72°C, 1 minute, 5 cycle, 3) 94°C, 30 seconds, 70°C, 30 seconds, and 72°C, 1 minutes, 5 cycle, 4) 94°C, 30

seconds, 68°C, 30 seconds, and 72°C, 1 minutes, 20 cycle, 5) 72°C, 10

minutes.

   Subcloning and DNA sequencing: PCR products (the murine

immunoglobulin gamma 2b chain CH1 region derived fragment and the

5   murine immunoglobulin kappa chain CL region derived fragment) were

subcloned into the pCRII vector (TOPO cloning, Invitrogen) and submitted to

UCSF Molecular Bioresource Center to analyze the DNA sequence.

   SEQ ID NO:1 is the DNA sequence of m166 heavy chain mRNA, SEQ

ID NO:2 is the amino acid sequence of the m166 heavy chain (IgG II$_b$), SEQ

10   ID NO:3 is the DNA sequence of the m166 light chain mRNA, and SEQ ID

NO:4 is the amino acid sequence of the m166 light chain. Figs. 6A, 6B and 7

examine the sequences and supply more detail.

Commercial Implications

   One could use the antibody sequence to produce recombinant single

15   chain antibodies that may block PcrV and could also utilize the sequence in

gene delivery experiments, where one would deliver eukaryotic vectors that

will then lead to the production of single chain antibodies in animals for

prolonged periods. Finally, the sequence could be utilized to humanize the

murine monoclonal antibody to produce a product that can be utilized in

20   human patient care. One of skill in the art would look to standard methods

such as grafting the antigen binding complementarity determining regions

(CDRs) from variable domains of rodent antibodies on to human variable

domains in order to create a humanized antibody.

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